to users of heavy rainstorm climatology in the design and operation of water control structures.

A summary and conclusions pertaining to various phases of the present study are included in Section 8. Point rainfall frequency relations for 61 locations in the state are shown in Appendices A through E.

Acknowledgments

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1. TEMPORAL CHANGES IN HEAVY RAINFALL FREQUENCIES IN ILLINOIS

A major use of historical precipitation data has been to develop rainfall frequency relations for partial and total storm periods of various durations ranging from a few minutes to as much as 10 days. These relations are used primarily in designing water-related structures such as urban storm sewer systems, but they also have applications in other fields in which assessment of heavy rain events is essential (e.g., agriculture, climate change, and weather modification).

Hydrometeorologists have fit various statistical distributions to historical precipitation data to derive various design values such as the 24-hour rainfall expected to occur on the average of once every 5, 10, or 100 years. Derivations of such values have traditionally been based on the assumption that the historical sampling period has year-to-year variations, but that it is essentially stationary, without major temporal fluctuations or long-term trends during the typical design period of 50 to 100 years for most water-related structures (Yevjevich, 1977). Hydrometeorologists who have developed these frequency values usually have employed all available historical data, and their results reflect the length of period sampled.

Most users desiring rainfall frequency values rely on U.S. Weather Bureau Technical Paper 40 (Hershfield, 1961), which provides average relations throughout the United States. In a few cases, more detailed data and different analytical approaches have been applied to obtain more comprehensive spatial distribution patterns on a regional or state basis, such as those derived for Illinois (Huff and Neill, 1959). Few updates of previously determined frequency relations have been performed in the last 35 years, and, in general, the earlier studies, which are in widespread use today, remain the primary sources of frequency values.

In an earlier preliminary study by Huff and Changnon (1987), 1901-1980 data for 22 Illinois precipitation-reporting stations were used to investigate the possibility of a climatic trend in the distribution of heavy rainstorms in Illinois. Huff and Changnon compared the frequency distributions of l-day and 2-day rainfall amounts, for recurrence intervals of 2 years to 25 years, for two 40-year periods, 1901-1940 and 1941-1980. They found substantial rainfall increases during the second 40-year period (1941-1980) for each recurrence interval tested in the northern part of the state, smaller increases in the west and central portions, and a slight decrease in the extreme southern and southeastern parts. Another study of Illinois climatic fluctuations by Changnon (1984a) revealed sizable shifts in precipitation and other weather conditions, including thunderstorms.

This line of inquiry was pursued further in our development of Illinois frequency relations from 1901-

1983 data, based on 61 precipitation-reporting stations having complete or nearly complete records for the entire sampling period. Another purpose of this additional study of the two 40-year periods was to ascertain the stability of the isohyetal patterns of heavy rainfall distribution in the present century.

Approach to the Problem

The 61-station sample was used to investigate the properties of the frequency distributions of maximum 24-hour and 48-hour rainfalls derived for the two 40-year periods (1901-1940 and 1941-1980) used in the earlier preliminary study. Analytical techniques developed in previous Illinois research on heavy rainstorms (Huff and Neill, 1959) were applied in the present study because they are still considered appropriate for solving the various problems involved in determining useful and reliable estimates of rainfall frequency distributions.

Frequency distributions were derived from the partial-duration series of rain events for each of the 61 stations. Frequency values were obtained from "best-fit" curves derived for each station. Although none of the several statistical distributions tested in this study and in the earlier Huff-Neil1 study provided an acceptable fit of the data at all stations, a log-log fitting provided the best fit in a majority of the cases. This method provided an excellent tit in more than 90% of the cases in the range of recurrence intervals from 2 to 25 years. A flattening of the log-log curve was typical for recurrence intervals of 50 to 100 years. A steepening of the curve was typical for recurrence intervals of less than 1 year.

Daily rainfall amounts at the 61 reporting stations were converted to maximum 24-hour and maximum 48-hour rainfall through use of transformation factors. The transformation factor for daily rainfall (1.13) was derived by Hershfield (1961), and the 2-day factor (1.02) was developed by Huff and Neil1 (1959) from Illinois recording raingage data .

Findings Relevant to Climatic Fluctuations and Related Trends

In general, the results of the expanded study support the earlier findings of Huff and Changnon (1987). This is illustrated in figure 1, which shows the distributions of the ratios of the 1941-1980 rainfall amounts to the 1901-1940 amounts for 24-hour maximum rainfall associated with an average recurrence interval of 2 years. Essentially, figure 1 indicates an increase in the intensity of P-year events in the northeastern (except for the extreme northeast), northwestern, western, and central parts of the state, and a very slight decrease in intensity over the southern, southeastern, and, to some extent, the eastern region of the state (in the Urbana-Charleston region). Within the state, 62% of the precipitation stations had ratios exceeding 1.00, and 36% had ratios exceeding 1.10.

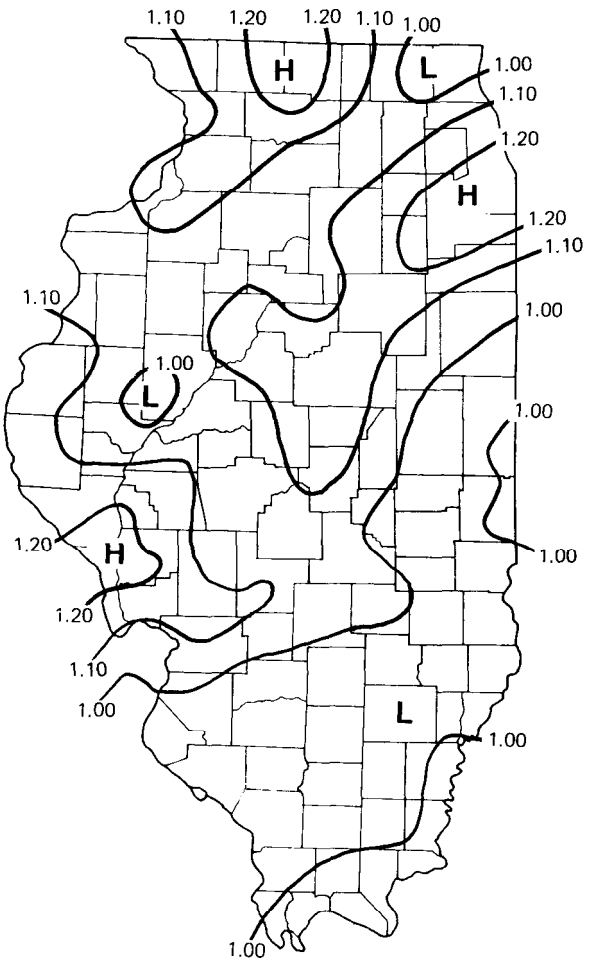

Figure 1. Ratios of 1941-1980 to 1901-1940 P-year, 24-hour rainfall amounts

The pattern in figure 1 was maintained for 24-hour maximum rainfall associated with 5-year, 10-year, and 25-year recurrence intervals. That is, highs and lows in the ratio patterns were found in approximately the same locations as for the 2-year patterns.

Figure 2 shows the distributions of ratios for 48-hour maximum rainfall associated with a recurrence interval of 2 years. The spatial pattern is very similar to the 24-hour pattern in figure 1, with highs and lows occurring in essentially the same regions of the

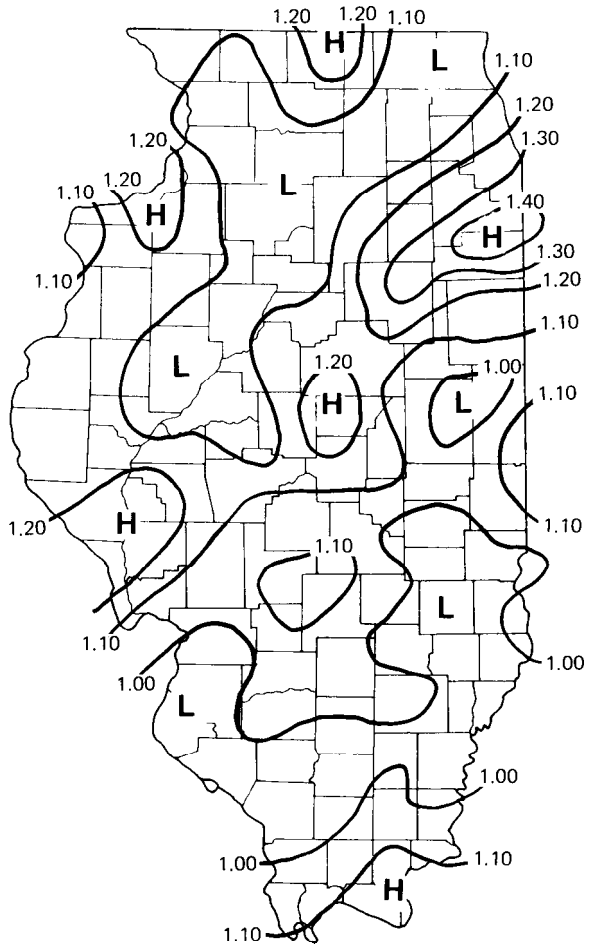

Figure 2. Ratios of 1941-1980 to 1901-1940 P-year, 48-hour rainfall amounts

state. The high in the Chicago-Kankakee-Pontiac area of northeastern Illinois is a little more pronounced for the 48-hour rainfall distributions. A weaker high in extreme southern Illinois is also more pronounced on the 48-hour map. Overall, the average ratios for the state were 1.06 for the 24-hour storm period and 1.09 for the 48-hour period. In the case of the 48-hour rainfall, approximately 68% of the precipitation stations had ratios exceeding 1.00, and 40% had ratios exceeding 1.10.

The spatial patterns exhibited in figures 1 and 2 are typical of those found for other recurrence intervals for both 24-hour and 48-hour storm rainfall. These patterns are in general agreement with and support the results of other Illinois studies of precipitation and floods in recent years. In a study of 1901-1980 data, Changnon (1985) found a gradual change to a wetter regime in Illinois during that 80-year period, and this was most pronounced in the last part (19651980) of his study period. In another study (Changnon, 1983), an increase in Illinois floods was detected in recent years, with the most pronounced change occurring in northeastern Illinois. Figure 1 shows increases of 20% or more in the 2-year, 24-hour rainfall amounts in the Chicago-Joliet region during the 1941-1980 period. This increase becomes even greater with 48-hour rainfall amounts, reaching values of 20 to 40% in the Chicago-Joliet-Kankakee region (figure 2).

Table 1 lists the average ratios of 1941-1980 to 1901-1940 24-hour rainfall amounts in each of the nine climatic sections of Illinois used by the National Weather Service (figure 3). In the northwestern and northeastern sections, in which the positive ratios are most pronounced, the ratios tend to become larger with increasing recurrence intervals. An upward trend in ratios is also indicated in the southeastern section, in which the ratio varies from 0.95 at the 2-year recurrence interval to 1.04 at the 25-year frequency. These upward trends suggest that the climatic trend or fluctuation in storm rainfall intensity has been most pronounced among the more severe of the heavy storms experienced during the two 40-year periods. However, because this effect was not indicated in the other six climatic sections, it may be possible that the northwestern, northeastern, and southeastern behavior represents a sampling vagary. The frequency values at the longer recurrence intervals are more subject to sampling error. For example, there are 20 independent 2-year events in each 40-year sample; this decreases to four in the case of lo-year events, and to two for 20-year occurrences.

Table 2 is similar to table 1 and shows average ratios of 1941-1980 to 1901-1940 48-hour rainfall amounts. Increasing ratios with increasing recurrence intervals are indicated in the northwestern, northeastern, and east southeastern sections. Slight downward trends (decreases) with increasing recurrence intervals are indicated in most other sections. In general, the 48-hour trends agree well with the 24-hour trends.

A study of thunderstorm incidences over the 1901-1980 period revealed that stations in northern Illinois experienced increases of 10 to 20% during the latter 40 years of the period. In the south, however, minor decreases (5 to 10%) were experienced in the 1941-1980 period (Changnon, 1984a). These findings support those obtained in the heavy rainstorm analyses discussed in the preceding paragraphs.

Typical differences in the frequency distributions of 24-hour maximum rainfall between the two 40-year periods are illustrated for selected precipitation

Table 1. Ratios of 1941-1980 to 1901-1940 24-Hour Maximum Rainfall Amounts for Selected Recurrence Intervals in NWS Climatic Sections of Illinois

Recurrence interval (yrs)	*Average* ratio *for* given recurrence interval								
	NW	NE	W	c	*E*	*w s w*	*ESE*	SW	*SE*
2	1.12	1.12	1.07	1.08	1.04	1.09	0.98	0.96	0.95
5	1.13	1.16	1.07	1.09	1.06	1.11	0.96	0.97	0.95
10	1.14	1.16	1.07	1.06	1.03	1.14	0.98	0.99	1.00
25	1.17	1.20	1.01	1.02	1.04	1.11	1.05	0.99	1.04
Mean	1.14	1.16	1.06	1.06	1.04	1.11	0.99	0.98	0.98

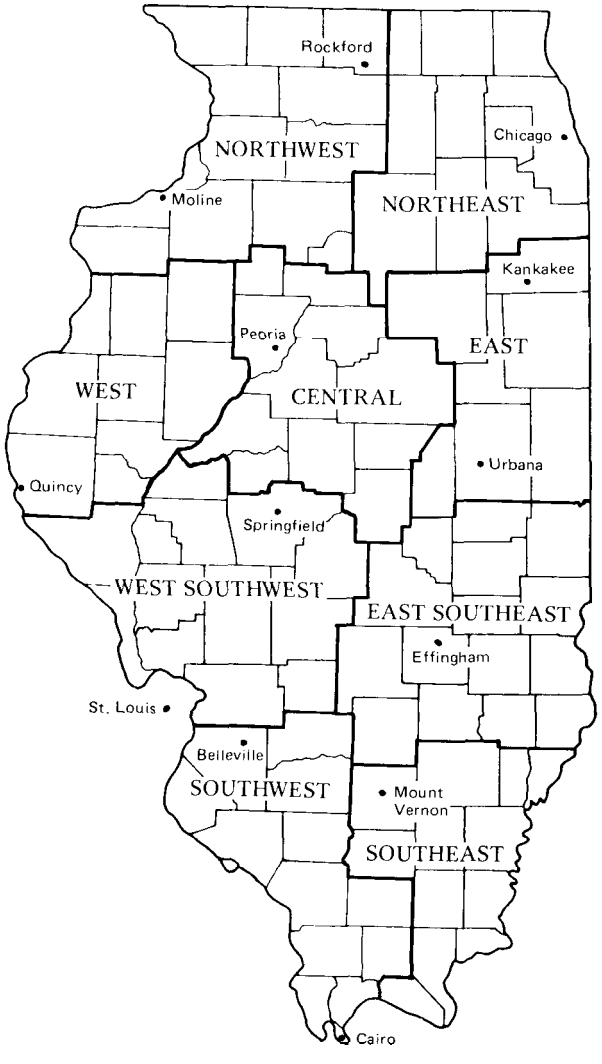

Figure 3. Illinois climatic sections adopted by the National Weather Service

stations **in figure 4.** The Rockford differences are relatively large and show the tendency among some stations for the 1941-1980 and 1901-1940 ratios to increase with increasing recurrence intervals. However, the Quincy curves do not indicate an increasing ratio with increasing recurrence interval, and the Peoria curves indicate a decreasing ratio with increasing recurrence interval.

Belleville is typical of the southern part of the state, where the 1901-1940 curves showed slightly heavier rainfall at the given recurrence intervals than indicated by the 1941-1980 curves. Thus, the differences between frequency distributions derived from the two 40-year sampling periods varied substantially within the state, as was discussed previously in conjunction with figures 1 and 2 and tables 1 and 2.

Tables 3 and 4 further illustrate the effect of climatic variations between the two 40-year periods and, consequently, their importance to hydrologists and others using frequency distributions derived from historical data. To develop table 3, 24-hour maximum rainfall was determined for 2-, 5-, and lo-year recurrence intervals from the 1941-1980 curves for the six selected stations illustrated in figure 4. For each recurrence-interval value, the corresponding recurrence interval for that rainfall was determined from the 1901-1940 curves. For example, at Rockford the 2-year rainfall value from the 1941-1980 curve corresponded to the 5-year value from the 1901-1940 curve. The 1941-1980 values for 5-year and lo-year recurrences at Rockford corresponded to 15-year and 35-year recurrence intervals, respectively, on the 1901-1940 curves. Smaller, but still relatively large, differences are indicated for Kankakee, Quincy, Peoria, and

Table 2. Ratios of 1941-1980 to 1901-1940 Maximum Rainfall Amounts for Selected Recurrence Intervals in NWS Climatic Sections of Illinois

Recurrence interval (yrs)	*Average ratio for given recurrence interval*								
	NW	*NE*	*W*	*C*	*E*	*WSW*	*ESE*	*SW*	*SE*
2	1.09	1.17	1.13	1.13	1.17	1.11	0.99	0.98	1.02
5	1.13	1.19	1.11	1.13	1.19	1.12	0.99	0.95	1.00
10	1.13	1.20	1.08	1.13	1.18	1.11	1.00	0.94	0.99
25	1.17	1.20	1.03	1.09	1.15	1.07	1.01	0.94	0.94
Mean	1.13	1.19	1.09	1.12	1.17	1.10	1.00	0.95	0.99

The relationships presented in table 3 are shown for 48-hour storm periods in table 4. The results are very similar to those for the 24-hour storm periods. Thus, at Rockford, the 2-year recurrence-interval value based on 1941-1980 data is equivalent to the 6-year recurrence interval based on 1901-1940 data. Likewise, the 5-year recurrence obtained from 1941-1980 data is equivalent to the 15-year value obtained from the 1901-1940 sample, and the lo-year recurrence from 1941-1980 data is equal to the 31-year value based on 1901-1940 data.

The results of these analyses indicate that hydrologic designs based on the 1901-1940 data for a given recurrence interval would have substantially underestimated the rainfall intensity for that recurrence interval during the 1941-1980 period over much of the state. For example, at Rockford (figure the 5-year expectancy for maximum 24-hour rainfall is 3.27 inches on the basis of 1901-1940 data. The 1941-1980 curve indicates that the average 5-year value is 4.05 inches. At Peoria, the 5-year recurrences are 3.55 and 4.05 inches, respectively, for the 1901-1940 and 1941-1980 data. At Quincy, the 5-year values are 3.73 and 4.45 inches, respectively.

In summary, this phase of the 40-year comparisons indicates a substantial change in the intensity of heavy rainstorms in the latter 40-year period. For a given recurrence interval, the 24-hour rainfall intensity was greater, on the average, over the northern and central portions of the state during 1941-1980, but was slightly less in the southern portions of Illinois.

These findings show that an adjustment should be made to incorporate this change into the derivation of heavy rainfall frequency relations from the 61-station, 83-year record for 1901-1983.

Temporal Stability of Isohyetal Patterns

An examination of isohyetal patterns for selected recurrence intervals shows that most major features were similar in the two 40-year periods (1901-1940 and 1941-1980). This is illustrated in figure 5, which displays the isohyetal patterns of 24-hour rainfall with a recurrence interval of 2 years. Both maps show 1) distinct highs in the extreme western and southern portions of the state, and 2) a low extending northeast to southwest along or in the vicinity of the Illinois River basin and northeastward into extreme northeastern Illinois. The major difference between the two maps is the presence of a 1941-1980 high extending southwestward from its most pronounced stage in the Chicago-Joliet-Kankakee area of northeastern Illinois to the vicinity of Decatur in the central part of the state and Belleville in southwestern Illinois. This high is apparent only in the Belleville area on the 1901-1940 map.

Figure 6 shows the isohyetal patterns for the two 40-year periods for rainfall with a recurrence interval of 5 years. These isohyetal patterns also show distinct highs over extreme southern and western Illinois and a low extending from the extreme northeastern part of the state southwestward along or in the vicinity of the Illinois River valley, in agreement with the 24-hour patterns shown in figure 5.

The 1941-1980 pattern, similar to that in figure 5, shows a high extending southwestward from the Kankakee area to southwestern Illinois. The 1941-1980 high in northeastern Illinois is centered near a region that has experienced increased flooding in recent years according to Changnon (1983). The isohyetal patterns in figures 5 and 6 are typical

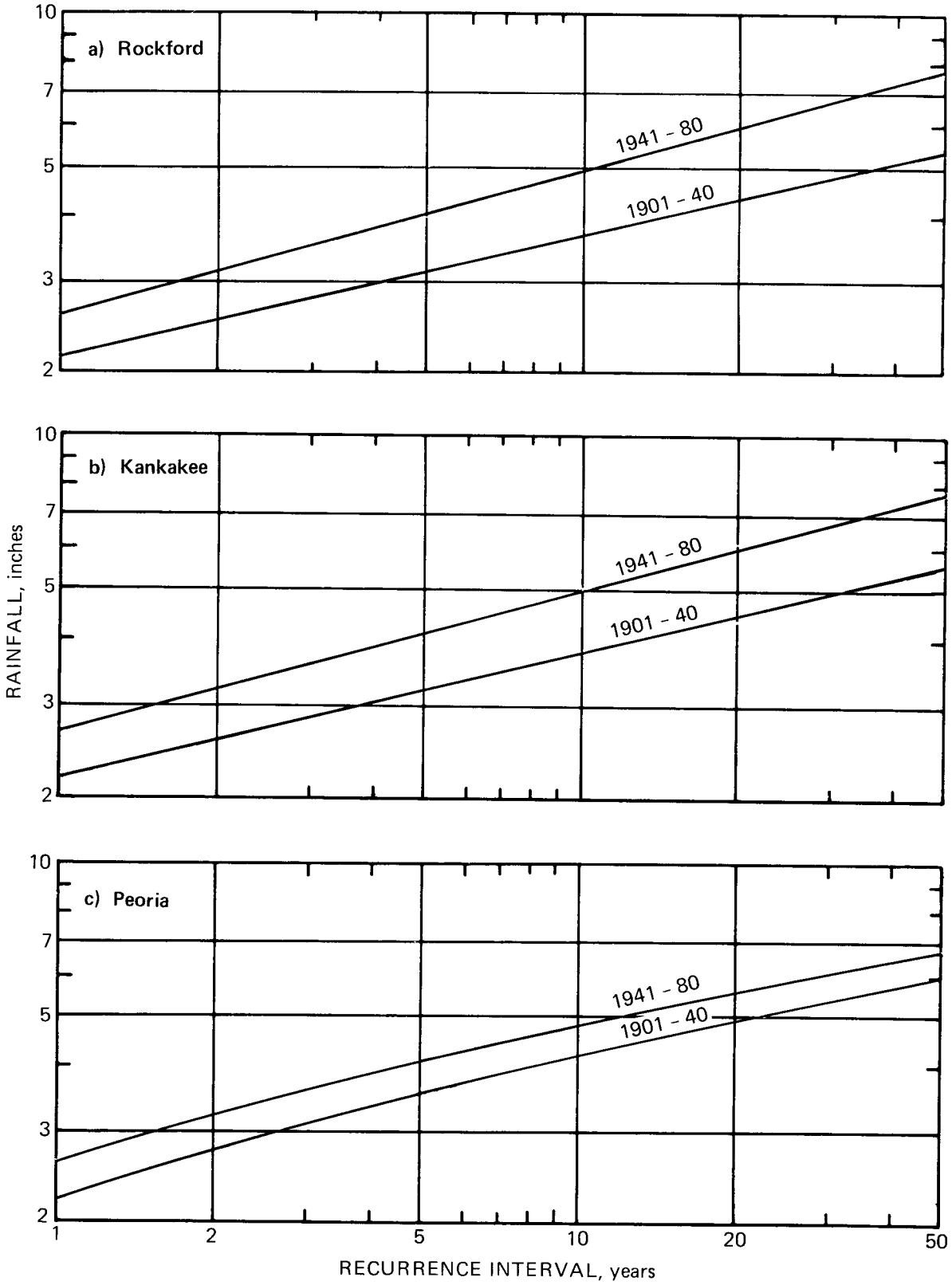

Figure 4. Frequency distributions of maximum 24-hour rainfall at selected stations in 1901-1940 and 1941-1980

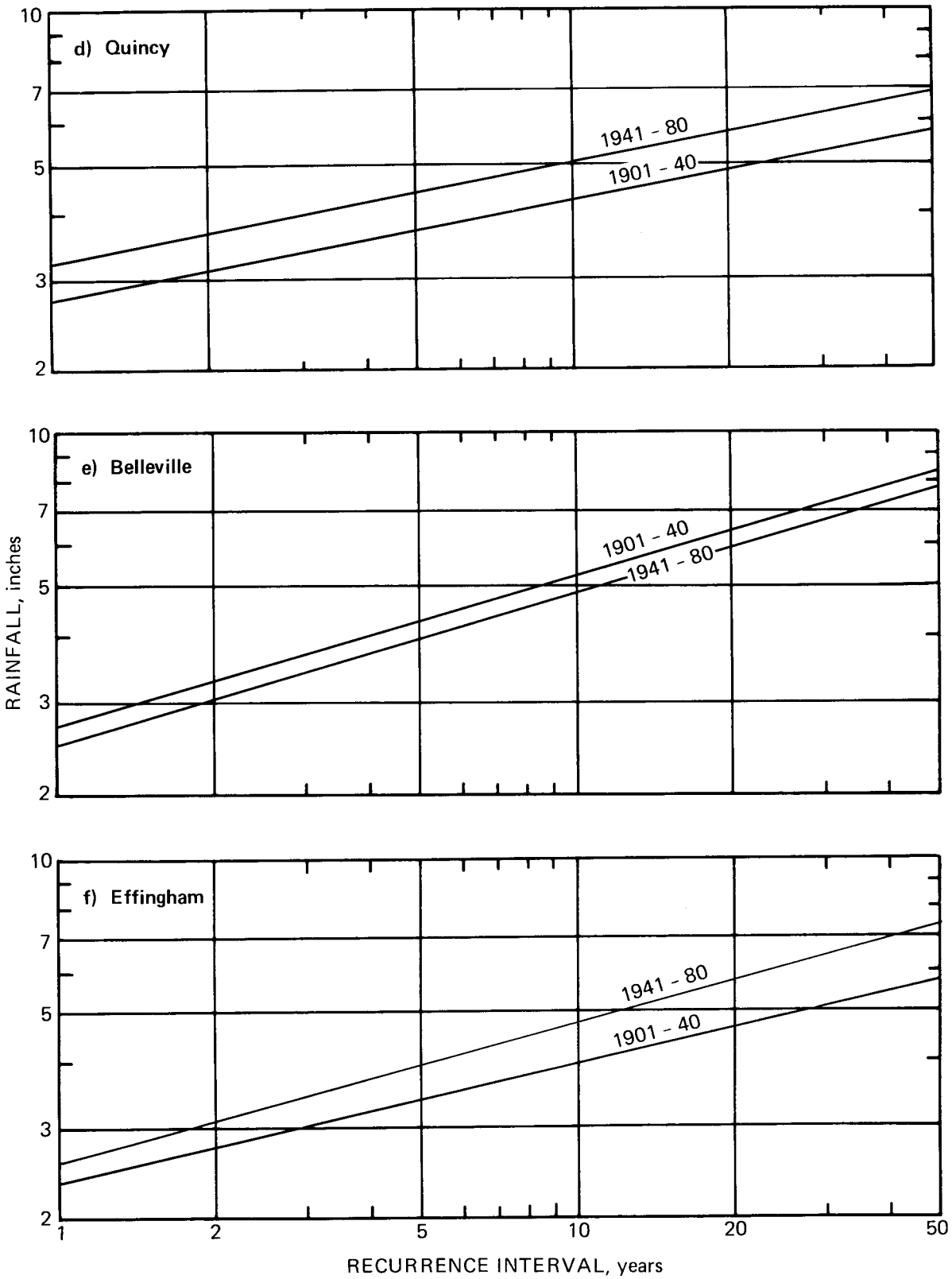

Figure 4. Concluded

Table 3. Variations in Recurrence Intervals for 24-Hour Maximum Rainfall from Frequency Curves Based on 1901-1940 and on 1941-1980 Data

Recurrence interval from 1941-1980 curves	*Equivalent recurrence interval from 1901-1940 curves for selected locations*					
	Rockford	*Kankakee*	*Peoria*	*Quincy*	*Belleville*	*Effingham*
2	*5*	*5*	*3+*	*5*	*2-*	*3+*
5	*15*	*16*	*9*	*13*	*4*	10
10	*35*	*35*	*17*	*27*	*8*	*21*

Table 4. Variations in Recurrence Intervals for 48-Hour Maximum Rainfall from Frequency Curves Based on 1901-1940 and on 1941-1980 Data

Recurrence interval from 1941-1980 curves	*Equivalent recurrence interval from 1901-1940 curves for selected locations*					
	Rockford	*Kankakee*	*Peoria*	*Quincy*	*Belleville*	*Effingham*
2	*6*	*5*	*3*	*8*	*2-*	*3+*
5	*15*	*18*	10	*17*	*4*	11
10	*31*	*49*	*22*	*32*	*8*	*25*

of those found for other recurrence intervals for 24-hour and 48-hour maximum rainfall.

The pronounced high in extreme southern Illinois is to be expected in view of its climatic and topographic properties. This region normally experiences the longest period of convective rainfall within the state, extending from early spring to late fall; even in winter, convective storms are not unusual. The region also has a relatively high frequency of thunderstorms (Changnon, 1957). Convective precipitation, dominated by thunderstorms, is most commonly associated with heavy rain events in Illinois. Furthermore, the Shawnee Hills, located in this region, have been found to intensify the natural rainfall (Huff, Changnon, and Jones, 1975).

The high in western Illinois is to be expected because this area also lies in a region of relatively high thunderstorm frequency (Changnon, 1957). Furthermore, the Ozark Mountains in Missouri southwest of this area are a source of storm development and intensification, and these hills are frequently crossed by storm systems moving into western and southwestern Illinois. For events of very short duration, primarily of three hours or less, Water Survey studies have shown an increase in the frequency and intensity of heavy rainfall amounts extending northeast, east, and southeast of St. Louis. This phenomenon is related to urban effects on the precipitation processes (Changnon et al., 1977).

The 1941-1980 high extending southwestward from the Chicago-Joliet-Kankakee area is closely aligned with a region of relatively frequent cold-front passages in summer, and these storm events frequently spawn heavy rainfalls (Chiang, 1961). The low in extreme northeastern Illinois (figures 5 and 6) may be associated with Lake Michigan's dampening effects on warm-season precipitation. The low in the vicinity of the Illinois River valley, which is quite pronounced in both 40-year periods, is likely associated with topographic factors and with the valley's normally downwind location with respect to the climatically and topographically favored regions of development and intensification of heavy rain events in western and southwestern Illinois.

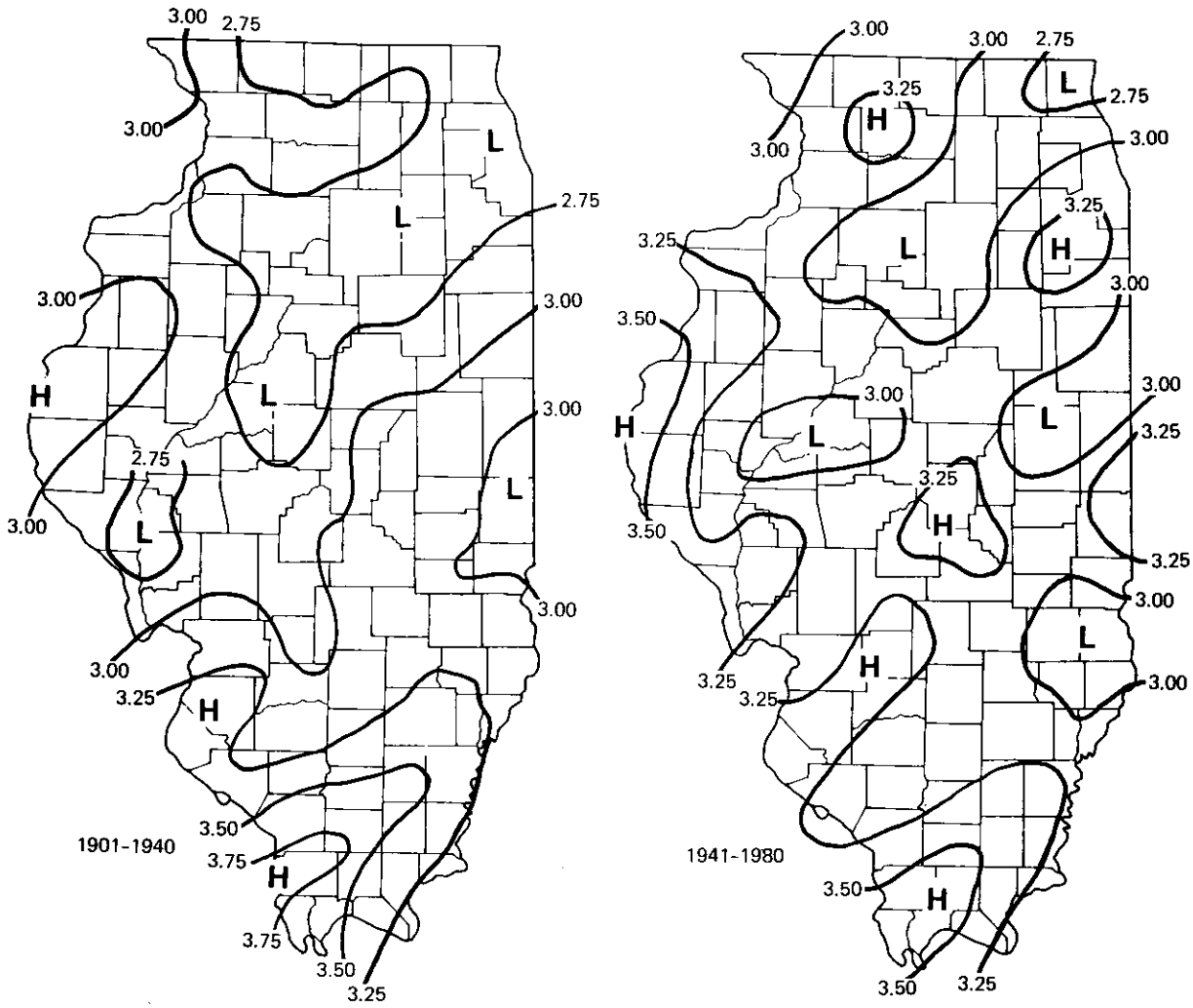

Figure 5. Isohyetal patterns of 2-year, 24-hour rainfall (inches) based on 1901-1940 and 1941-1980 data

The results of the foregoing analyses indicate that during the 1901-1980 period the spatial (isohyetal) patterns of heavy rain events remained stable with respect to the locations of highs and lows in the statewide distribution. However, the intensity of heavy rainfall events has increased over much of the state during recent years, as indicated by this study and those of Changnon (1983, 1985). As a result of overall findings from the 40-year comparisons, it was decided that the 83-year sample (1901-1983) should be used as a basis for updating the frequency distributions of heavy rain events in Illinois. However, Lamb and Changnon (1981) and others have shown that the most recent precipitation events are the best for judging the nature of events in the near future. Therefore, it was also decided to include an adjustment to the frequency distributions derived from the 1901-1983 data, based on findings from the 40-year comparison study. This adjustment is discussed further in Section 3, which is devoted to the development of frequency distributions from the 1901-1983 data.

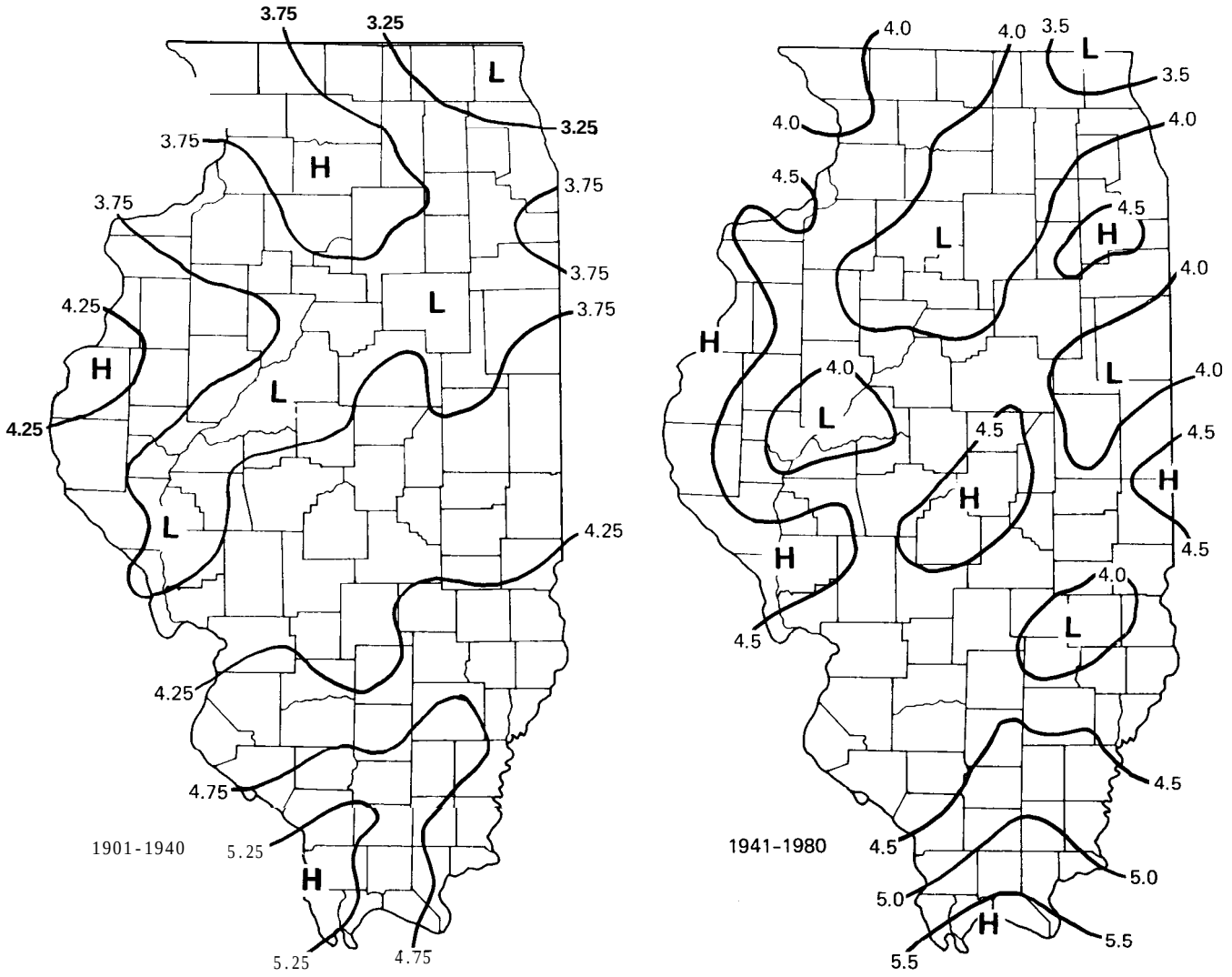

Figure 6. Isohyetal patterns of S-year, 48-hour rainfall (inches) based on 1901-1940 and 1941-1980 data

2. COMPARISON OF INDEPENDENT 10- AND 20-YEAR PERIODS

In the previous section, results of a study of two 40-year periods (1901-1940 and 1941-1980) were presented. The results indicated that the frequency/ intensity regime of heavy storms was considerably different in the two periods. For given recurrence intervals (2 years, 5 years, etc.) and rainfall durations (1 hour, 12 -hours, 24 hours, etc.), the 1941-1980 data indicated heavier rainfall amounts. Thus the data indicated a climatic change or trend in the frequency distributions of heavy rainstorms. In this section, the existence of a climatic trend is explored further through comparison of data for four 20-year and eight lo-year independent periods in the 80-year sampling period at the 61 Illinois precipitation-reporting stations.

Trend Analyses of 20-Year Periods

Computations were made of the 80-year trends (1901-1980) in l-day to 10-day rainfall amounts, based on frequency distributions derived for each of